How to Build a Gravitational-wave Detector

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1st Galileo-XuGuangqi meeting

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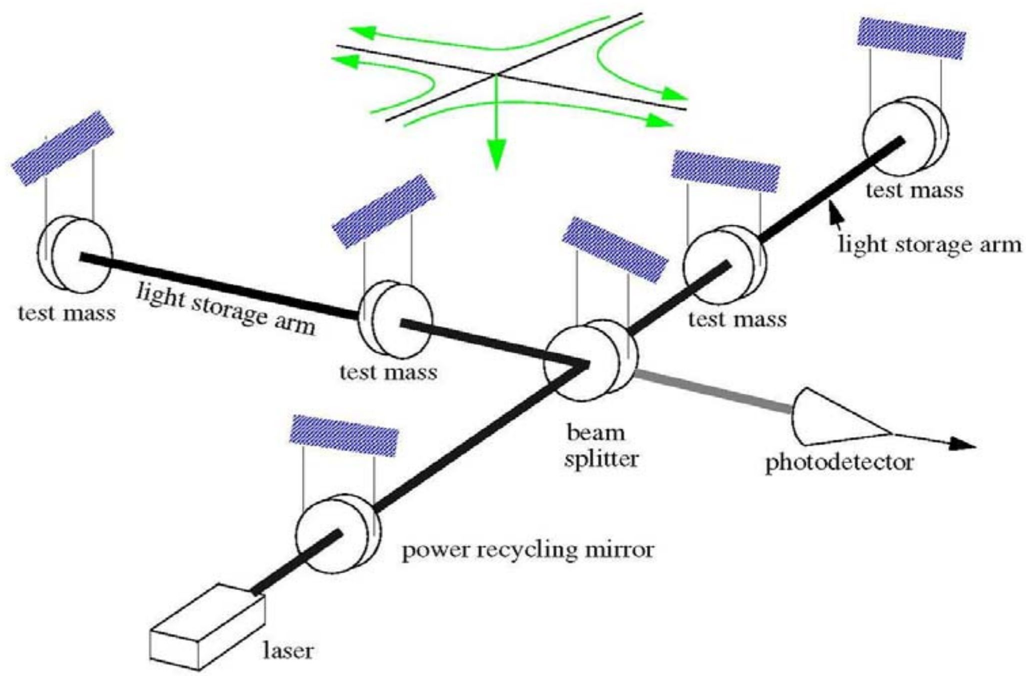
Outline of Talk

- Focus on Ground-based Laser Interferometers
- The Challenges
  - » Sensitivity / Noise Sources
  - » Organization and Management
  - » Integration as the Key Element
- Closing thoughts

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses (in horizontal plane) for frequencies $f >> f_{pend}$

$$h = \Delta L / L$$



Terrestrial detector

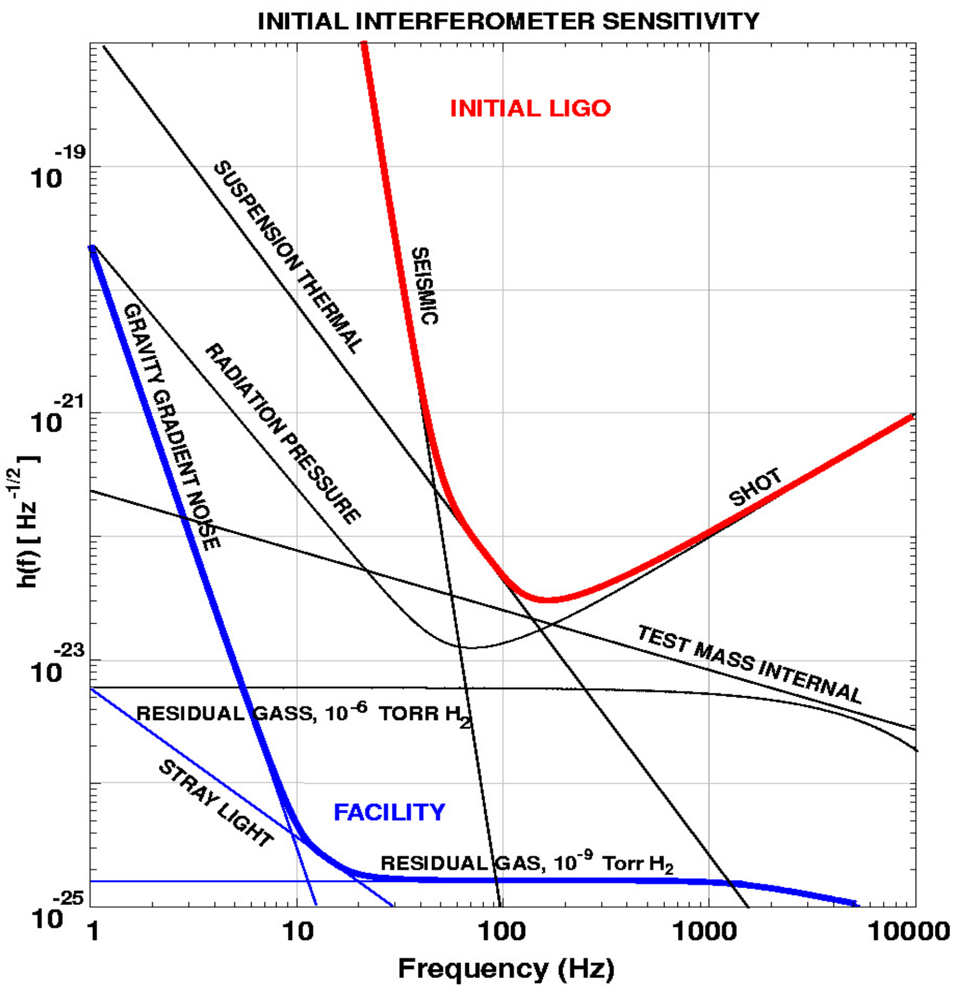
For $h \sim 10^{-22} - 10^{-21}$

$L \sim$ 4 km (LIGO)

$\Delta L \sim 10^{-18}$ m

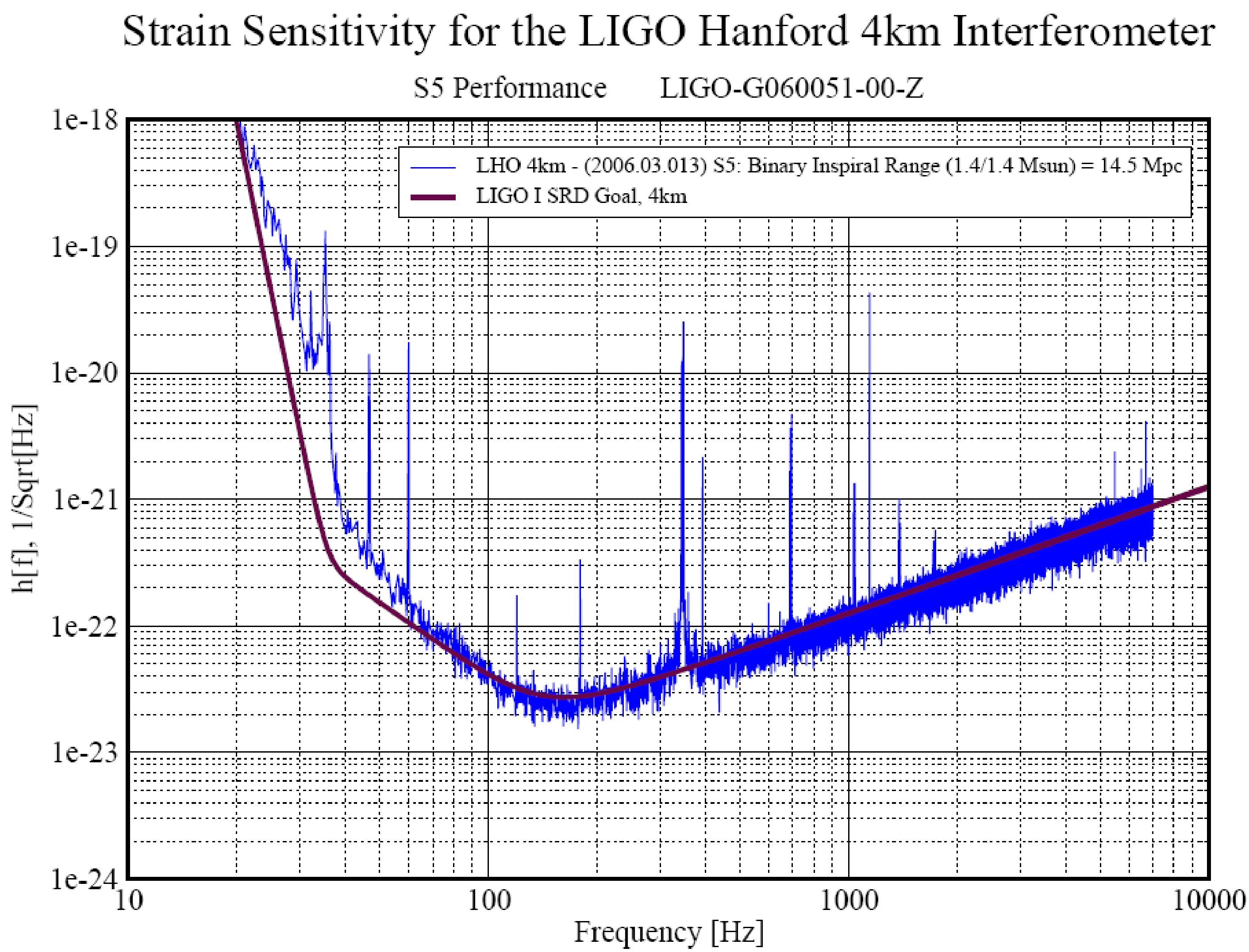
10^{-18} m is 1/1000 the diameter of an atomic nucleus

Initial LIGO Sensitivity Goal



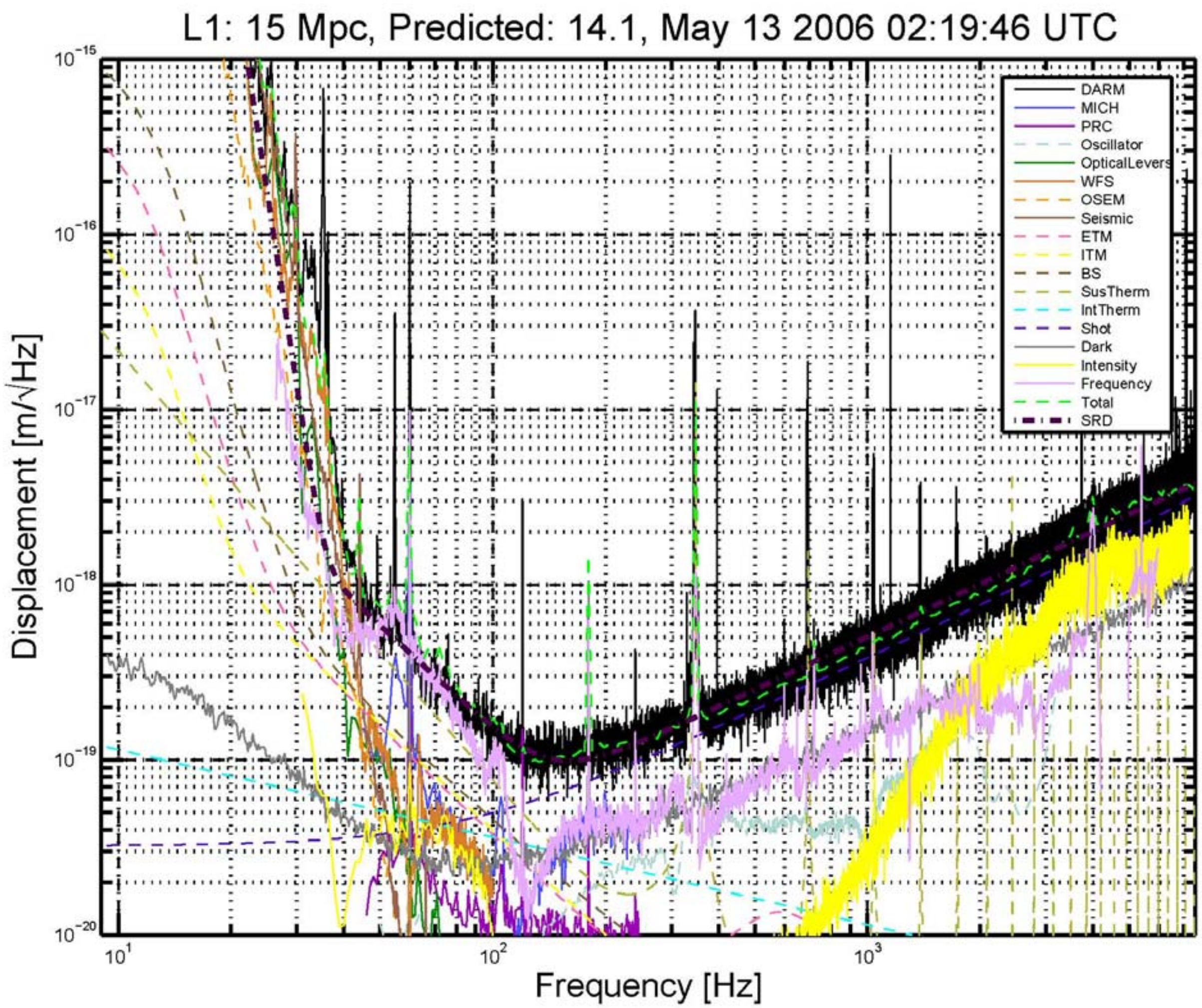
- Strain sensitivity $<3 \times 10^{-23}$ 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon shot noise
  - » Residual gas
  - » Laser frequency noise
- Displacement Noise
  - » Seismic motion
  - » Thermal noise
  - » Radiation pressure

LIGO Sensitivity



A Real Noise Budget

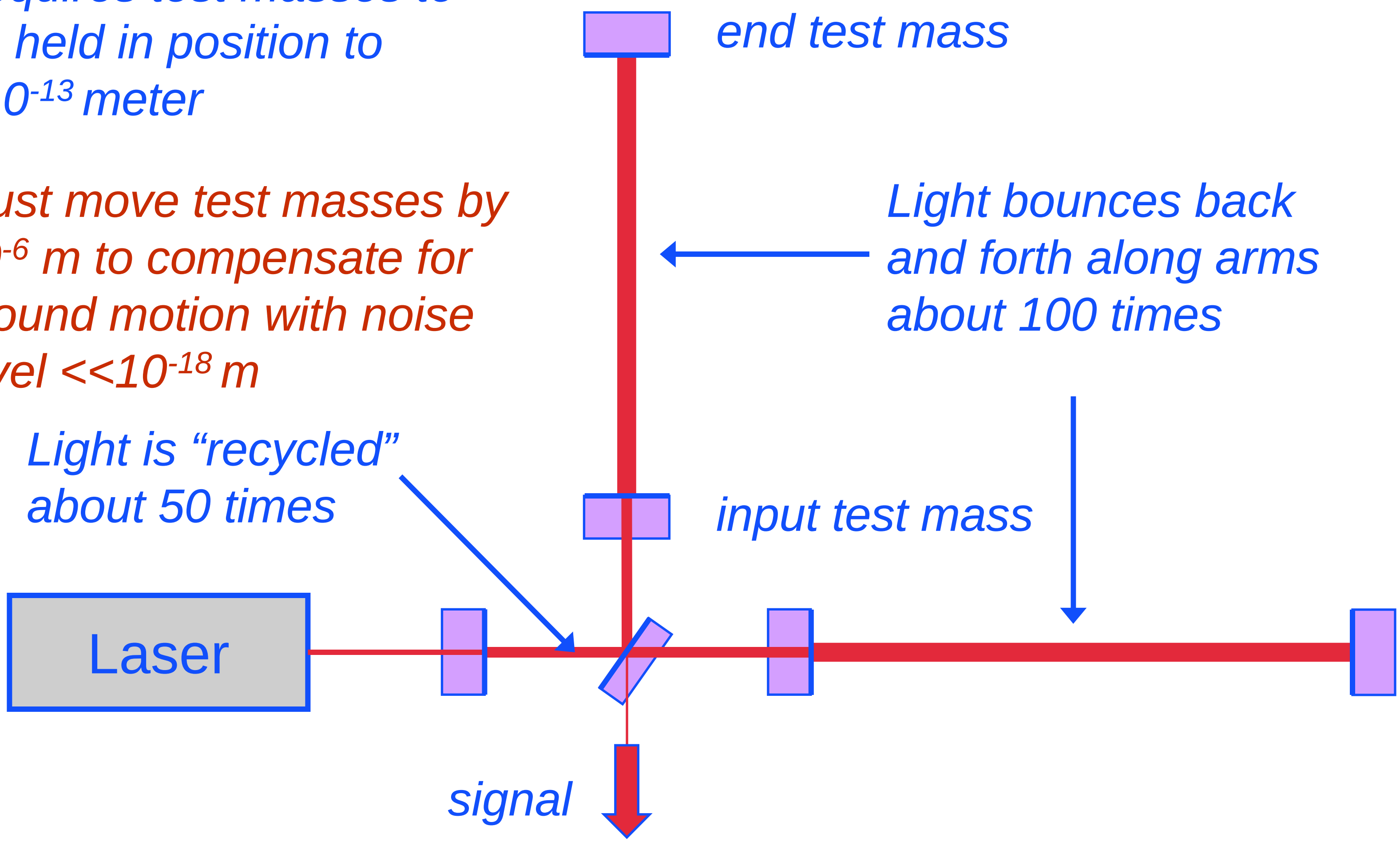
Most of the work goes into noise sources that never show up in talks or papers!



Example: Control Systems

Requires test masses to be held in position to ~10^{-13} meter

Must move test masses by 10^{-6} m to compensate for ground motion with noise level <<10^{-18} m



The Technical Challenge

- Noise sources are sometimes divided into "fundamental" and "technical" categories
  - » "Fundamental" are those that physicist like to work on
  - » "Technical" are the ones that someone else ought to fix
- There are many more technical noise sources than fundamental ones
  - » Time and effort to uncover and reduce them is also much larger
- Everything has to be done right

Organization and Management

- Cost of a GW detector for the international network is of the order of US$100M
  - » Varies based on the accounting standards of different countries (salaries included or not, cost differences between countries, etc.)

- Effort required on the order of 500 person-years
  - » Need effective management structures to organize and coordinate effort of this scale

Management Techniques

- Work Breakdown Structure
  - » Exactly what it says it is: a "tree" structure to break the work into manageable parts
- Essential components of a WBS element
  - » Definition of technical scope
  - » Budget
  - » Schedule
  - » Contingency
  - » Other resources needed

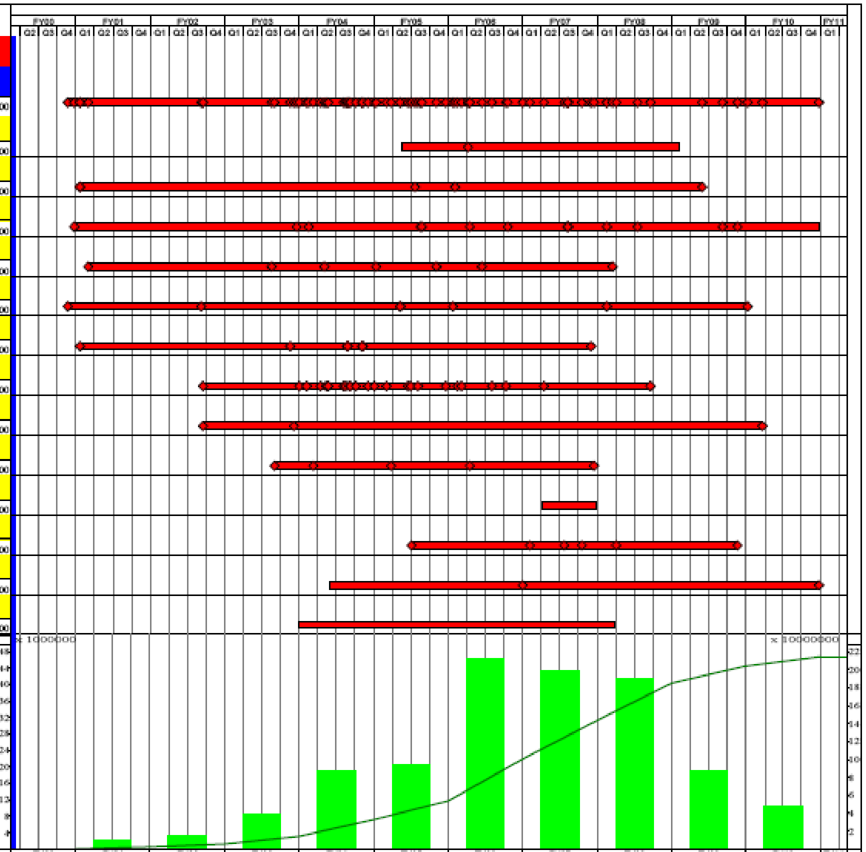
LIGO.4.04 Prestabilized Laser (PSL)

- LIGO.4.04.1 PSL Subsystem Management
- LIGO.4.04.2 PSL R&D
  - LIGO.4.04.2.1 High Power Laser R&D - Caltech
  - LIGO.4.04.2.2 High Power Laser R&D - Stanford
  - LIGO.4.04.2.3 High Power Laser R&D - ACIGA
  - LIGO.4.04.2.4 High Power Laser R&D - GEO
- LIGO.4.04.3 PSL Design
  - LIGO.4.04.3.1 PSL Conceptual Design/Requirements
  - LIGO.4.04.3.2 PSL Preliminary Design
    - LIGO.4.04.3.2.1 System Design/Simulation
    - LIGO.4.04.3.2.2 Laser Design & prototype development
    - LIGO.4.04.3.2.3 Laser Performance Characterization/Acceptance
    - LIGO.4.04.3.2.4 Frequency Noise Suppression Design
    - LIGO.4.04.3.2.5 Intensity Noise Suppression Design
    - LIGO.4.04.3.2.6 Prototype Testing
    - LIGO.4.04.3.2.7 Safety Requirements/Design
  - LIGO.4.04.3.3 PSL Final Design
    - LIGO.4.04.3.3.1 System Design/Simulation
    - LIGO.4.04.3.3.2 Laser Design & prototype development
    - LIGO.4.04.3.3.3 Laser Performance Characterization/Acceptance
    - LIGO.4.04.3.3.4 Frequency Noise Suppression Design
    - LIGO.4.04.3.3.5 Intensity Noise Suppression Design
    - LIGO.4.04.3.3.6 Prototype Testing / Testbed Fabrication
    - LIGO.4.04.3.3.7 Safety Requirements/Design
- LIGO.4.04.4 PSL Fabrication
  - LIGO.4.04.4.1 Laser Fabrication
  - LIGO.4.04.4.2 Optomechanical Fabrication
  - LIGO.4.04.4.3 Electronics Fabrication
  - LIGO.4.04.4.4 Testbed Fabrication
  - LIGO.4.04.4.5 First Article Testing
  - LIGO.4.04.4.6 Assembly

Work Breakdown Structure (WBS)

- Example

	Orig Dur	Early Start	Early Finish	Budgeted Cost
LIGO				
LIGO.4 Advanced LIGO				
Subtotal	2,524	21AUG00	22SEP10	214,883,284.00
+ LIGO.4.01 Facility Modifications (FAC)	935	18FEB05	10NOV08	4,182,087.00
+ LIGO.4.02 Seismic Isolation (SEI)	2,088	18OCT00	28FEB09	44,331,341.00
+ LIGO.4.03 Suspension (SUS)	2,503	20SEP00	22SEP10	39,093,848.00
+ LIGO.4.04 Prestabilized Laser (PSL)	1,763	28NOV00	13DEC07	17,277,320.00
+ LIGO.4.05 Input Optics (IO)	2,286	21AUG00	08OCT09	4,839,775.00
+ LIGO.4.06 Core Optics Components (COC)	1,718	18OCT00	30AUG07	19,920,832.00
+ LIGO.4.07 Auxiliary Optics (AOS)	1,502	17JUN02	17JUN08	15,084,931.00
+ LIGO.4.08 Interferometer Sensing and Control (ISC)	1,881	17JUN02	21DEC09	12,811,747.00
+ LIGO.4.09 Data Acq., Diag., Network & Supervisory Control	1,076	02JUN03	14SEP07	9,157,563.00
+ LIGO.4.10 Support Equipment (SUP)	189	02JAN07	28SEP07	1,500,000.00
+ LIGO.4.12 LIGO Data Analysis System (LDAS)	1,097	01APR05	18AUG09	12,487,116.00
+ LIGO.4.13 Installation (INS)	1,649	24FEB04	22SEP10	24,828,860.00
+ LIGO.4.14 Project Management (PM)	1,061	01OCT03	28DEC07	9,387,864.00



Resource/Cost Profile Legend

Total of All Resources

Total early cost per Year (Current Estimate)

Current estimate curve

Earned value curve

Planned value curve

Detail scale (left): X 1000000

Cumulative scale (right): X 10000000

Start Date	01DEC99
Finish Date	22SEP10
Data Date	01DEC99
Run Date	23MAY03 00:54

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L000
BL Advanced LIGO

Sheet 1 of 1

Baseline Rev. 05.22.03

LIGO Laboratory Program

Adv. LIGO Summary

Management Techniques

- Management team must show that it will use appropriate tools to monitor and assess progress
  - » Shows wise stewardship of the public's money
  - » Funding agencies will require it

How much has been spent compared with what has been accomplished?

What is the current estimate for the schedule and how does that affect the costs?

How are you dealing with the unexpected? (Contingency management)

- Not the skills of a typical physicist
  - » Must be learned on the job
- Important to draw in an experienced project manager

System Engineering and Integration

- To build a big scientific facility you need to break it down into manageable pieces…

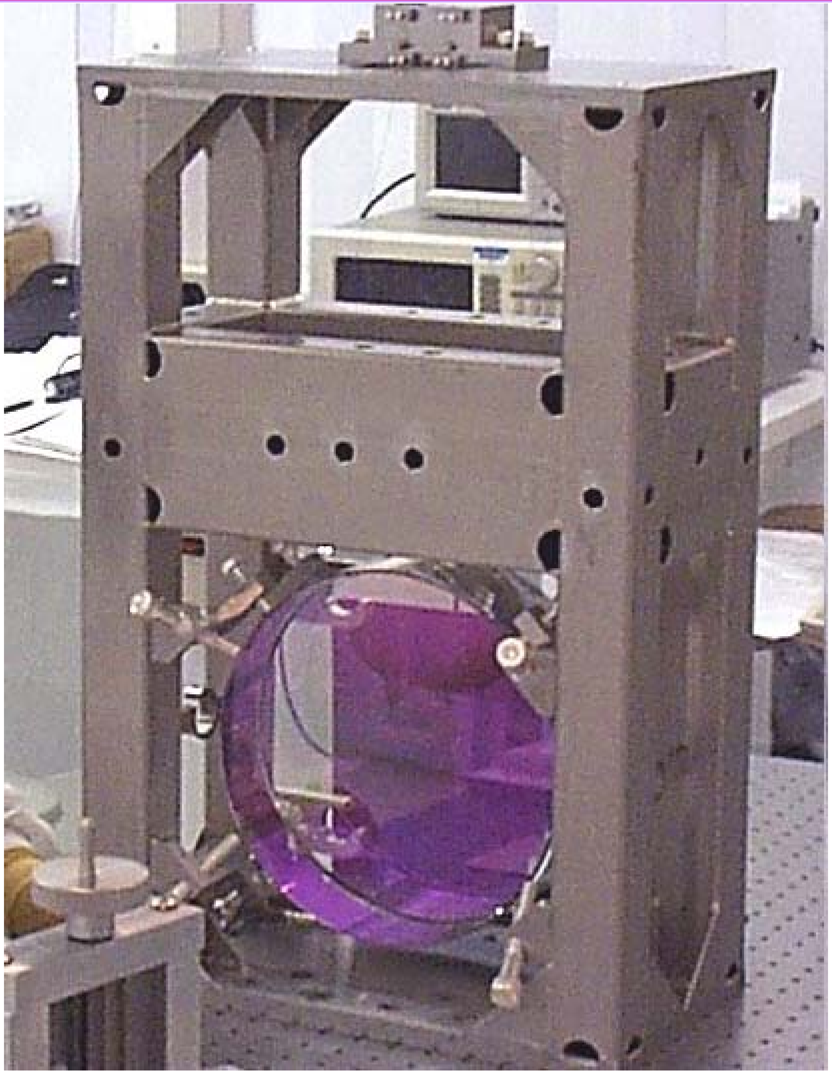
  But to make it work, you need to bring it together and make all the pieces work together

- Strong system engineering group to define subsystem requirements, manage performance and interfaces, and resolve inconsistencies and conflicts
  - » SW's observation: Practical physicists can be very effective system engineers
- A particularly significant challenge for GW interferometers because of their inter-connected nature
  - » Components must fulfill diverse requirement

Interferometer Mirror

Optical Requirements

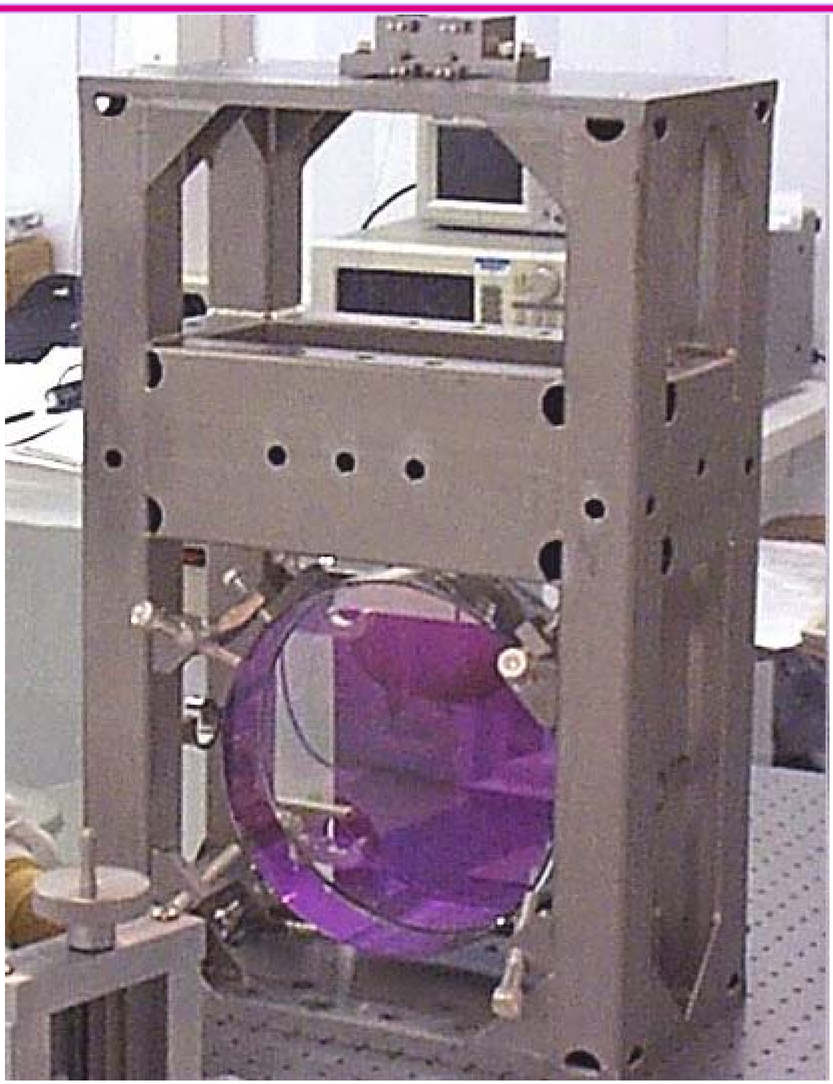
- Surface Figure
  < 1 nm rms
- Radius of Curvature
  matched < 3%
- Material homogeneity
  < 5 x 10^{-7}
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}



Test Mass

Mechanical Noise Requirements

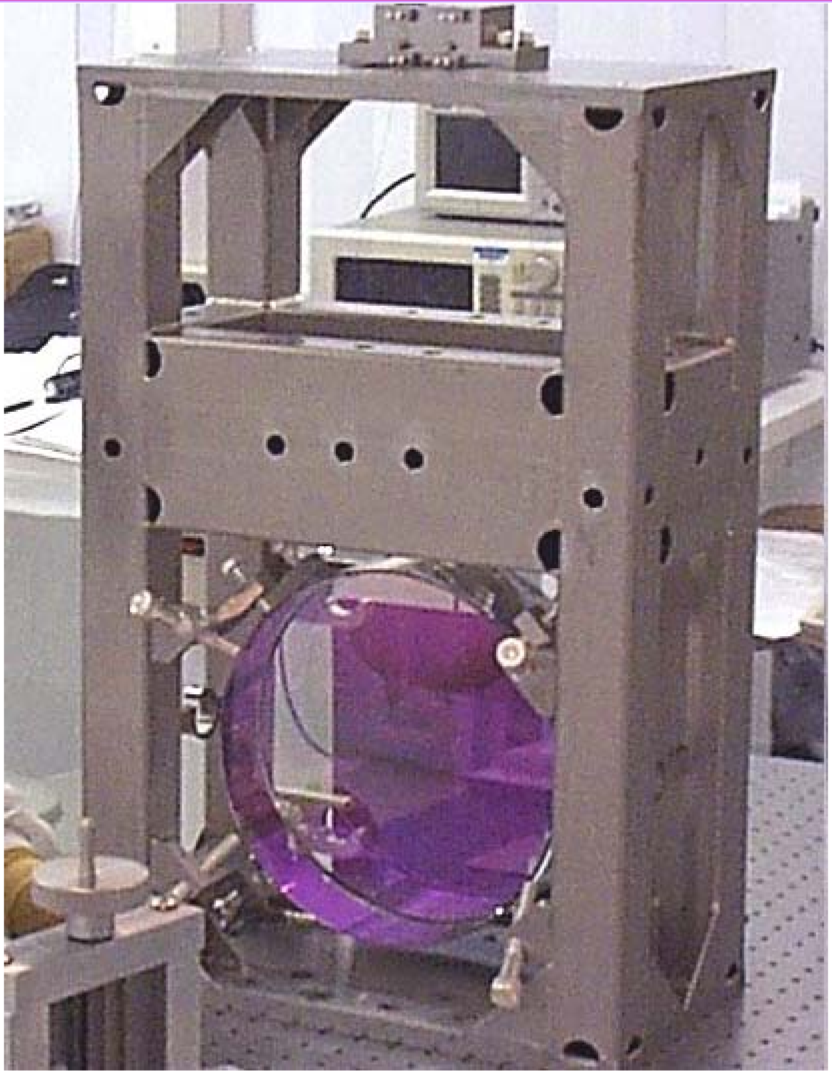
- Optical surface must reproduce the motion of a free body in space
- Vibration isolation
- Low noise suspension
  - » Attachment techniques
- Low thermal noise
  - » Size: 25 cm Diameter, 10 cm thick
  - » Internal mode Q's > 2 x 10^6
  - » Mechanical properties of coating



Component in a Servoloop

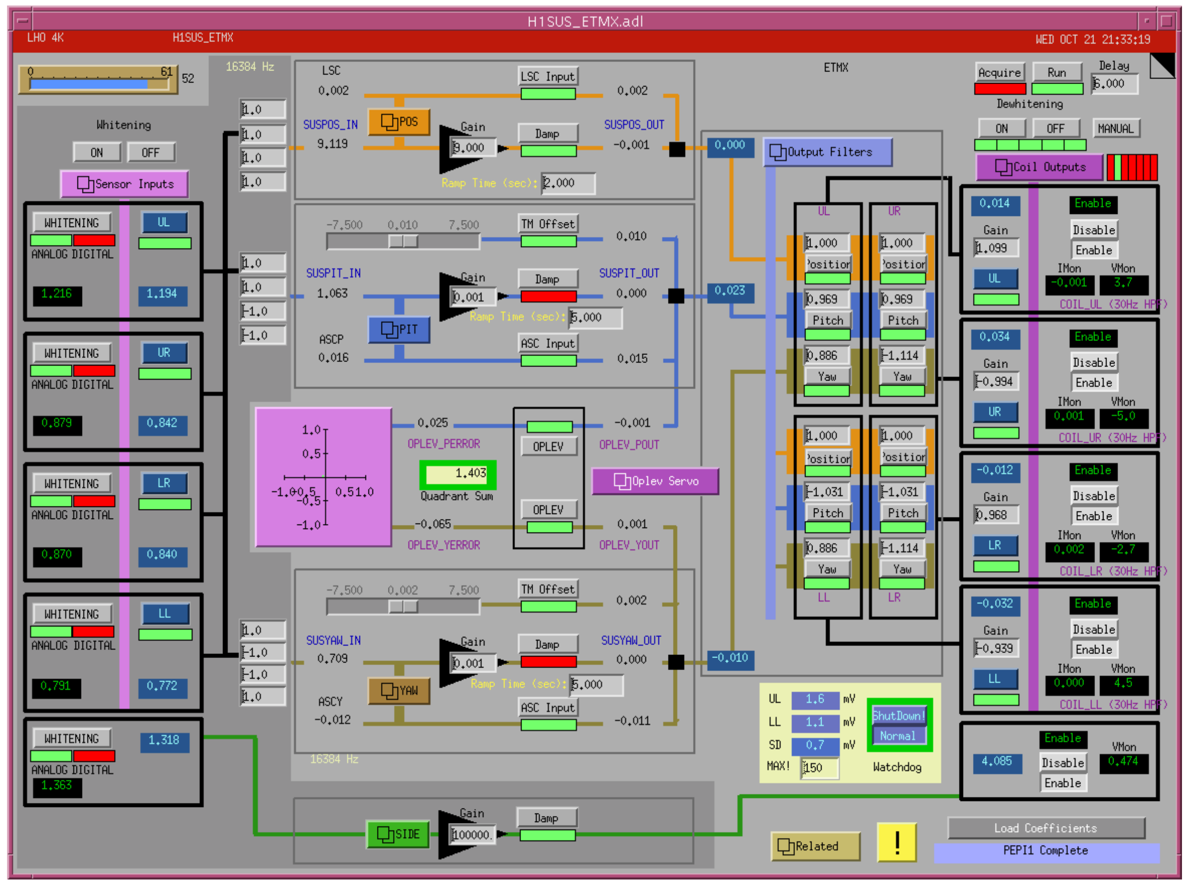
Servo Actuator Requirements

- Need to apply forces to control position and orientation
  - » Coupling of angle to length
  - » Noise from control system
  - » Resonances (!)
  - » Effect of reaction forces



Integration and Commissioning

- GW Interferometers are complex instruments
  - » Up to ~200 servo loops, all needing to operate optimally
  - » As many as 10000 control settings and readbacks
- Interactions are complex, and they are unique to the particular configuration
- Changes in one part of the apparatus can ripple through in subtle and unforeseen ways



Final Thoughts

- Have I taught you how to build a gravitational wave detector?
  - » No, a 30 minute talk is far too short!
  - » I have tried to lay out the key issues in the broadest context
- Success requires not only the tools of experimental physicists, but also skilled managers and engineers
- If there is an effort to build a detector in this region, then there is a vibrant and interested international community that wants to help